PHGN598

Introduction to Nuclear Reactor Physics

Summer 2006

Part I: Physics Fundamentals

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Part II: Nuclear Reactors

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Nuclear Physics Fundamentals

A. Survey of Nuclear properties
   - nuclear constituents and their forces
   - nuclear size and energy
   - semiempirical mass formula
   - shell model basics

B. Radioactivity
   - decay processes, notation, stability, and energetics
   - conservation laws, decay chains
   - law of radioactive decay

C. Nuclear reactions
   - characterization and energetics
   - flux, rate, and cross section

D. Interactions of radiation with matter
   - charged particles and ionization
   - gamma processes
   - neutrons

E. Applications
   - environmental issues, nuclear energy and weapons
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Introduction: The physicist's prejudice

Overall goal: "Scientific Literacy"

Knowledge and thinking skills necessary to construct an appropriate understanding of a given physical situation.

Philosophical viewpoint: Newtonian Paradigm

{Particles; Forces; Law of Motion}

{understanding; prediction; engineering}

"Scientific Literacy"
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Scientific Literacy as applied to Nuclear processes

{(2 protons, 2 neutrons);
(nuclear force law);
{quantum mecanics})

{prediction for mass of 4He}

\[ E = mc^2 \Rightarrow \]

\[ Q = 2m_p c^2 + 2m_n c^2 - m_{He} c^2 \]
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Where does Nuclear physics live?

What is the scale (order of magnitude) of energy and length for nuclei?
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Standard Model of Particle Physics

Quarks:
- u up
- c charm
- t top
- d down
- s strange
- b bottom

(x 3 colors)

Leptons:
- e electron
- \( \mu \) muon
- \( \tau \) tau
- \( \nu_e \) neutrino
- \( \nu_\mu \) neutrino
- \( \nu_\tau \) neutrino

Particles:

Forces:
- Strong
  - gluons
  - quarks only
- Electromagnetic
  - photon (gamma)
  - quarks +
  - \( Z, W \)-bosons
- Weak
  - all
- Gravity
  - ?graviton?

Dynamical Law:
Quantum mechanics

Planck's constant: \( \hbar = 6.3 \times 10^{-34} \text{ J} \cdot \text{s} \)

\[
\hbar = h \frac{\pi}{2n} \rightarrow 0 \quad \text{\( n \rightarrow \infty \)} \quad \text{\( \rightarrow \) Newton's Classical Mech.} 
\]
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Nuclear Constituents ("nucleons")

neutrons and protons
(baryons "heavies")

<table>
<thead>
<tr>
<th>Object</th>
<th>(Quark) Structure</th>
<th>Mass (MeV)</th>
<th>Charge (e)</th>
<th>Spin (ℏ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>(uud)</td>
<td>938.27</td>
<td>+1</td>
<td>1/2</td>
</tr>
<tr>
<td>neutron</td>
<td>(udd)</td>
<td>939.57</td>
<td>0</td>
<td>1/2</td>
</tr>
</tbody>
</table>

In Conventional units:

\[ m_p = 1.67 \times 10^{-27} \text{ kg} \]

\[ q_p = 1.6 \times 10^{-19} \text{ C} \]

\[ \hbar = 6.3 \times 10^{-34} \text{ J-s} \]

Useful combination: \[ \hbar c = 197.3 \text{ MeV-fm} \]
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Other particle players: electron and neutrino

Weak decay of the neutron:
\[ n \longrightarrow p + e^- + \bar{\nu} \]

- electron (\(e^-\)):
  - \(m_e = 0.511 \text{ MeV}/c^2\)
  - \(q_e = -1\)
  - \(s_e = 1/2\)

- neutrino (\(\nu\)):
  - \(m_\nu = 0 \text{ MeV}/c^2\)
  - \(q_\nu = 0\)
  - \(s_\nu = 1/2\)

- Quantum of electromagnetism: photon (gamma)
  \((m_\gamma = 0, q_\gamma = 0, s_\gamma = 1)\)

Quanta of the strong force: (mesons, \(\pi\), \(\rho\), \(\omega\),...)
\((m_\pi = 135 \text{ MeV}/c^2, q_\pi = +1, -1, 0; s_\pi = 0)\)

Notation: To indicate the antiparticle place a bar above symbol
\[ \bar{\mu}, \bar{\nu}, \bar{\rho}, (\bar{e} = e^+) \]
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Standard Model of Particle Physics

Quantum picture for forces: Quantum exchange of mediating particle

(Feynman Diagram)

\[ V_{12} = \frac{q_1 q_2}{r_{12}} \]

1 photon exchange = quantum explanation of Coulomb's Law
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Nucleon-Nucleon Force: Meson-Mediated

\[
V_{12} = -\frac{g_{\pi N}^2 e^{-m r_{12}^2/c^2}}{r_{12}}
\]

Characteristics of strong force:

1. Net attractive
2. Strong \( (g_{\pi N}^2 \approx 10) \)
3. Short range: \( \frac{\hbar \cdot c}{m_\pi c} = \frac{197.3 \text{ MeV} \cdot \text{fm}}{135 \text{ MeV}} \approx 1.4 \text{ fm} \)
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Nuclear Notation and Nomenclature

Total nucleon (mass) number

\[ A \quad \text{"Z"} \quad \text{example:} \quad ^{197}\text{Au} \]

Chemical symbol

\[ Z - \text{number of protons (determines chemistry)} \]

\[ A - \text{total number of nucleons (protons+neutrons)} \]
\[ (\text{determines mass}) \]

\[ N = A - Z \quad \text{- number of neutrons} \]

isotope - equal \( Z \) (chemistry same)

isotone - equal \( N \)

isobar - equal \( A \) (mass)
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Nuclear Size and Shape
Determined by Nuclear Force
and Pauli Exclusion Principle

Strong and attractive

Short range attraction

Shorter-range repulsion

\[ V_{nn} \]

\[ r \]

Bind like close-packed spheres.

Density \( \approx \) const.

\[ r_0 \] ("hard spheres")

"saturation"
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Implications of density saturation

\[ A = \rho_0 \frac{4\pi}{3} R^3 \]

Thus

\[ R \propto A^{1/3} \quad \text{or} \quad R = R_0 A^{1/3} \]

where \( R_0 = 1.2 \text{ fm} \) and is universal
Example problem:

What is the radius of $^{208}\text{Pb}$?

$R_{\text{Pb}} = 1.25 \times 208^{1/3} = 7.01 \text{ fm}$
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Energetics: Binding energy (BE)

\[ \text{BE} = \text{energy needed to break a nucleus up into free neutrons and protons.} \]

-or-

\[ \text{BE} = \text{energy released when a nucleus is formed from free nucleons.} \]

Using the relativistic mass-energy relation,

\[ M(A) < Z m_p + N m_n \]

The difference is the \( \text{BE}/c^2 \)
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The nuclear binding energy is defined:

$$BE(A,Z) = Z m_p + N m_n - M(A,Z)$$

proton mass  nuclear mass

For convenience however we use ATOMIC masses

$$BE(A,Z) = Z m_h + N m_n - M(A,Z)$$

hydrogen atom  atomic mass

Atomic mass unit (u) = $M(^{12}\text{C})/12$

$$u = 931.5 \text{ MeV}$$


Mass Excess: (tabulated in Appendix C)

$$\Delta = M(A,Z) - A \ u$$